ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT NUMBER: FHWA-AZ87-810

DEVELOPMENT OF GUIDELINES FOR SELECTING COST-EFFECTIVE DIAMOND INTERCHANGE CONTROL

State of the Art

Final Report

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August 1987

Prepared for:
Arizona Department of Transportation
206 South 17th Avenue
Phoenix, Arizona 85007
in cooperation with
U.S. Department of Transportation
Federal Highway Administration

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TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO. FHWA-AZ87-810	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE DEVELOPMENT OF GUIDELINES FOR SELECTING COST-EFFECTIVE DIAMOND INTERCHANGE CONTROL State of the Art		5. REPORT DATE August 1987 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) William R. McShane, Herbert S. Levinson, Vassilios Papayannoulis, Elena V. Shenk		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Transportation Training & Research Center Polytechnic University 333 Jay Street Brooklyn, New York 11201		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. HPR-PL-1(31) ITEM 810
12. SPONSORING AGENCY NAME AND ADDRESS ARIZONA DEPARTMENT OF TRANSPORTATION 206 S. 17TH AVENUE PHOENIX, ARIZONA 85007		13. TYPE OF REPORT & PERIOD COVERED Final Report December,1986-March,1987 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. ABSTRACT

This project provides information on the state of the art in the use of diamond interchanges, and recommendations for needed work.

This report contains several "rules of thumb" distilled from the work and from current practice, as well as a detailed review of existing sources.

The work was accomplished by (1) conducting an extensive review and evaluation of existing reports and literature, (2) discussing current practice and issues with engineers at several organizations and agencies, (3) drawing upon the experience and knowledge of the members of the project team, and (4) doing sketch analyses of some alternative designs.

The principal conclusion of the effort for Arizona DOT is that there are three critical elements to consider, and the existing literature and knowledge is deficient in information on two of these elements.

The three elements are:

1. The role of design in avoiding and/or inducing problems at diamond interchange configurations;
2. The need to consider the routing of major flows in deciding upon signal strategy;
3. The use of signal timing and optimization within the context of the first two elements.

The fact is that these are a heirarchy, and yet the literature (and the guidelines available to engineers) generally ignores the first two in favor of the third.

In accord with the contract, recommendations are made. The recommendations are that (1) specific work be done on Elements 1 and 2 above, and (2) guidelines and a "case book" be prepared for the practicing engineer, related to the above. Details are given in the report (Tables 1 and 2).

17. KEY WORDS Interchange, Diamond Interchange Configurations, Signal Phasing, Spillback, Optimization	18. DISTRIBUTION STATEMENT Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	55	

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DIAMOND INTERCHANGES: AN EVALUATION OF THE STATE OF THE ART AND OF CURRENT PRACTICE, WITH RECOMMENDATIONS

1. PROJECT ACTIVITIES AND OVERVIEW

This project was undertaken by the Transportation Training and Research Center (TTRC) of Polytechnic University for the State of Arizona, to provide information on the state of the art in the use of diamond interchanges, and to provide recommendations for needed work.

1.1 Project Activities

As part of this project, the project team addressed the subject by:

+ drawing on their own experience in traffic control, operations, and facility design;

+ extracting published material on the subject by use of the Transportation Research Information Service (TRIS) and National Technical Information Service (NTIS) computerized data bases via the DIALOG search service, and by other literature review;

+ assessing the current practice of engineering decision-making related to diamond interchange design and operation, by a series of telephone calls to agencies involved with diamond interchanges;

+ reviewing the literature comprehensively;

+ conducting "case studies" of several designs, as preliminary exercises to illustrate some of the recommendations, and to respond to the interest of Arizona DOT in comments on one design concept.

In conducting this work, the team members cited on the report cover were actively involved.

1.2 Historical Context

Figure 1 illustrates a set of typical "diamond" interchange configurations, including those with and without frontage road involvement.

Diamond interchanges generally have distinct advantages over more comprehensive designs (such as full cloverleaf interchanges) in space utilization, land cost, construction cost, and design simplicity.

Historically, in new construction in urban areas, the space and land cost aspects have often dominated to the point where diamond interchanges became commonplace. In rural areas, the low volumes at a particular interchange often made an unsignalized diamond interchange.

Such reasons have led to the present situation in which a significant percentage of all interchanges are diamond configurations.

Unfortunately, the situation which motivated or allowed the diamond interchange configuration does not remain static. Volumes grow, and left turn conflicts within the diamond often lead to substantial degradation in the quality of flow.

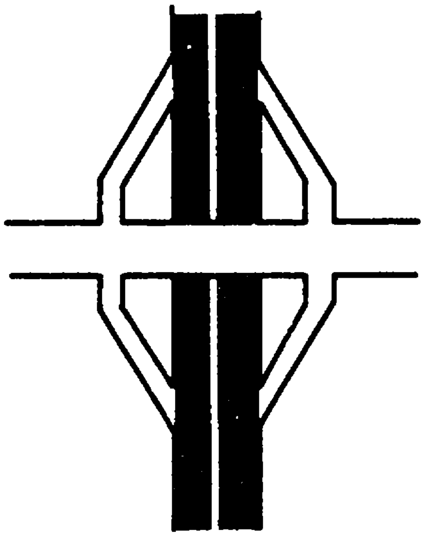
In urban areas, there may never have been a real question of "doing it differently", due to the lack of space. In rural areas, there might have been a choice, but the volume forecasts did not justify it. When such "rural" areas develop into suburbs or even development clustered around the interchange, the question of land acquisition for an expanded intersection is very often no longer an economic or political reality.

Thus, the issue often becomes (1) how to make diamonds work better within the existing space, and (2) how to build a better diamond.

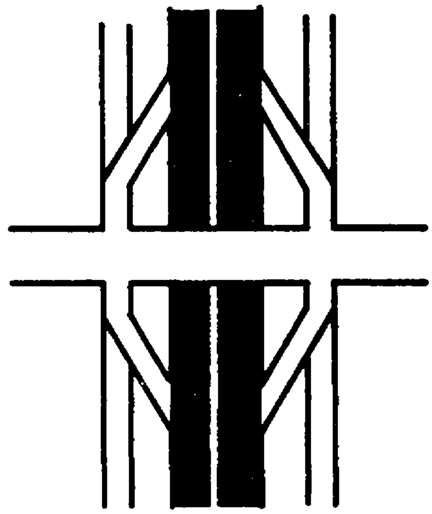
2. SUMMARY AND PRINCIPAL CONCLUSION

2.1 Summary of Literature

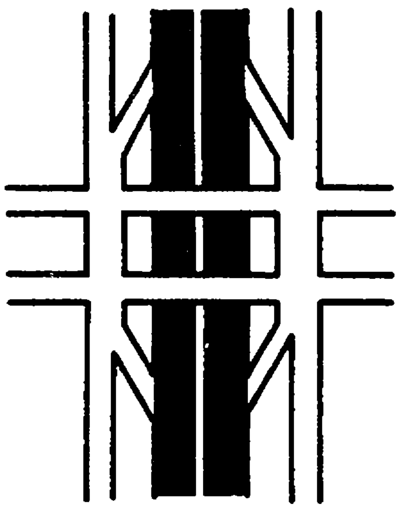
The literature is filled with issues related to the signalization and signal optimization of diamond interchanges. Indeed, this subject is addressed so extensively that one is tempted to conclude that (1) the real issue is strictly optimal signalization to make a diamond work, and (2) so much has been done that little remains to be done.



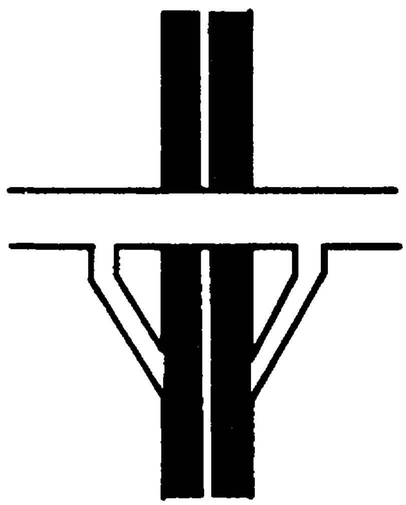
Full Diamond Interchange



Full Diamond Interchange
with Frontage Roads



Split Diamond Interchange



Half Diamond Interchange

Source: Ref [1].

FIGURE 1

SOME BASIC DIAMOND INTERCHANGE CONFIGURATIONS

This work addresses these issues in a context that we can best explain as a logical sequence of:

No Control --> Stop Signs --> Signalization --> More Sophisticated Signalization

This sequence is familiar to many traffic engineers, faced with annual increases in volume at an existing diamond interchange. The "more sophisticated signalization" involves actuated equipment, then microprocessor-based algorithms (e.g the diamond signal program for the Type 170 controller), and then issues related to special phasing plans and detectorization.

The literature which addresses these issues is summarized in Section 5 of this report. It is important, but is only one element of the consideration of diamond interchanges.

2.2 Principal Conclusion

The principal conclusion of the effort for Arizona DOT is that there are three critical elements to consider, and the existing literature and knowledge is deficient in information on two of these elements.

The three elements are:

1. **The role of design in avoiding and/or inducing problems at diamond interchange configurations;**

2. **The need to consider the routing of major flows in deciding upon signal strategy;**

3. **The use of signal timing and optimization within the context of the first two elements.**

The fact is that these are a heirarchy, and yet the literature (and the guidelines available to engineers) generally ignores the first two in favor of the third.

2.3 Illustration and Discussion

The following paragraphs illustrate each of the points cited above. A more comprehensive analysis must be done. This is addressed in the next item.

a. The Role of Design

Consider the two diamond interchange configurations of Figures 2 and 3. What are the relative advantages of the two?

The standard diamond configuration of Figure 2 has the obvious advantage of space, and of requiring only one highway bridge.

The configuration of Figure 3 may not be easily recognized as a diamond by some, particularly if it is imbedded in other development. However, it is indeed a diamond configuration.

The primary advantage of Figure 3 is that the left turn conflicts are removed from the north-south flow, and turned into a crossflow; refer to Figure 4.

Notice that as left turn volumes increase, the first configuration would be driven to a three phase operation. Further, conservative design would have required extra lanes (one or two in each direction) for the stored left turners on the highway bridge, in the constrained space, for either known or future volumes.

The configuration of Figure 3 does not require the storage on the bridge, nor does it have conflicting left turn volumes, as already cited. Further, it will be signalized as a set of two-phase signals. Refer to Figure 5, which makes this clear.

The potential advantages of two phase operation (versus three or four phase) and of avoiding left turn conflicts weigh strongly in favor of the second configuration, with the first still having apparent advantages in space utilization and in bridge cost.

However, note that the first design may require a very wide highway bridge (up to eight lanes, including left turn storage) whereas the second design requires two distinct structures whose combined width may be less than that of the first design.

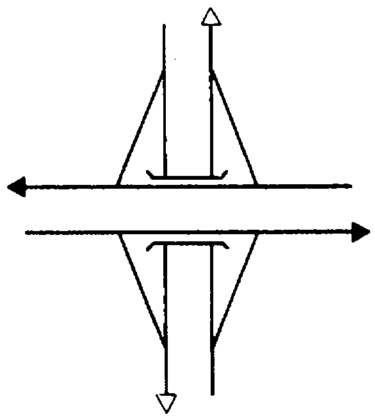


FIGURE 2

STANDARD DIAMOND INTERCHANGE

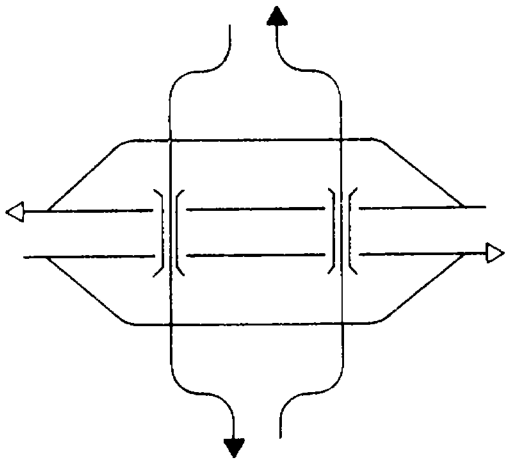


FIGURE 3

ANOTHER DIAMOND INTERCHANGE CONFIGURATION

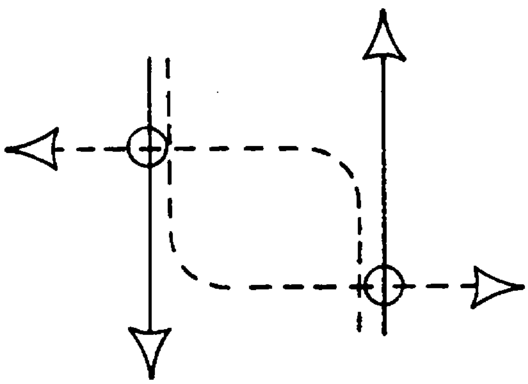


FIGURE 4

LEFT TURNS BECOME A CROSSFLOW

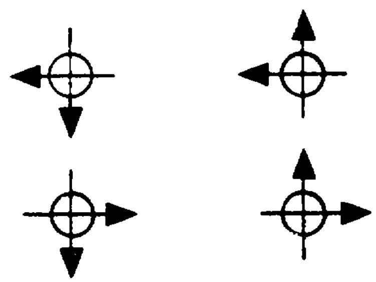


FIGURE 5

TWO PHASE SIGNALIZATION

Further, note that the interior land can be accessed by adding loops as indicated in Figure 6, making the total land removed from tax rolls less than might be anticipated.

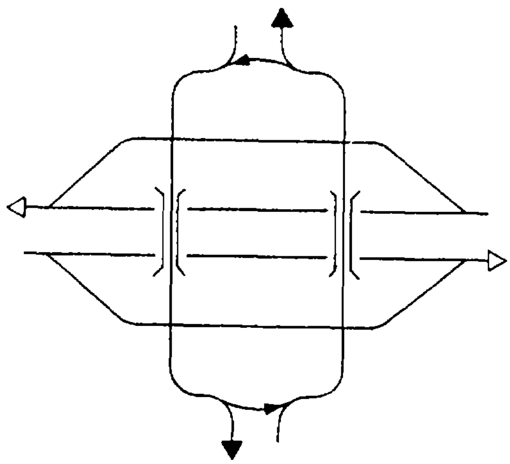


FIGURE 6

ASSURING INTERIOR LAND ACCESS IN THE SECOND DESIGN

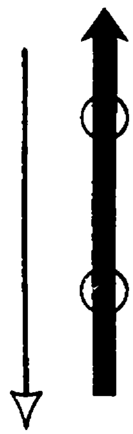
This illustration is but one way in which different diamond configurations have design versus operational tradeoffs which are vital to consider.

The information routinely available to design engineers and traffic engineers does not include (1) economic analyses of such tradeoffs, considering both initial capital costs and later annual traffic operational expenses, (2) a comprehensive list of common design alternatives, and (3) guidelines for the practicing engineer based upon such information.

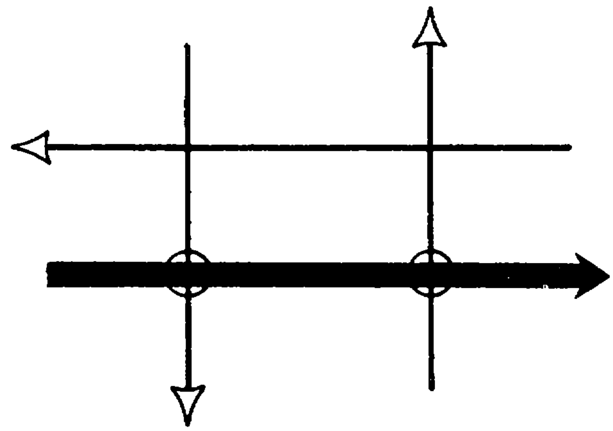
b. Need to Consider Traffic Routing of Major Flows

Many diamond interchanges involve major flows on the surface streets which require coordinated or platooned movement.

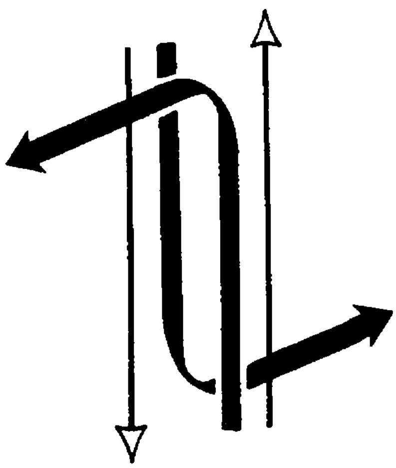
These flows are not always the through movements on the surface street perpendicular to the freeway, although this is common. Figure 7 illustrates some of the possible dominant flows. Note that in some cases,



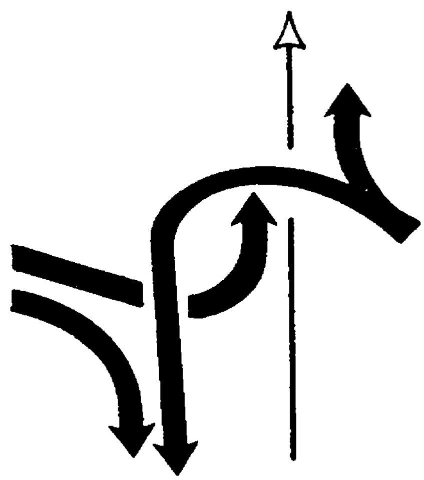
a. Cross Arterial Through Traffic Dominant



b. Frontage Road Serving as an Arterial



c. Flows to Freeway Dominate



d. Flows From Freeway Dominate

FIGURE 7

SOME OF THE FLOWS WHICH MAY INFLUENCE DIAMOND INTERCHANGE DESIGN, GEOMETRY, AND OPERATION

+ the cross arterial's through movements are dominant;

+ the frontage road serves as an arterial which must be coordinated in its own right;

+ the left turns to the freeway dominate;

+ the left turns from the freeway and/or frontage road dominate.

What is the significance of this? There are two principal consequences of such recognizing the above:

+ signal plans which "optimize" the performance within the diamond by introducing highly responsive control within the diamond may be extremely counterproductive, if the needs of the dominant major flows are ignored or disrupted.

The question of whether a diamond is best served by pretimed or actuated control is thus very much related to the existence (and types) of major surface street flows;

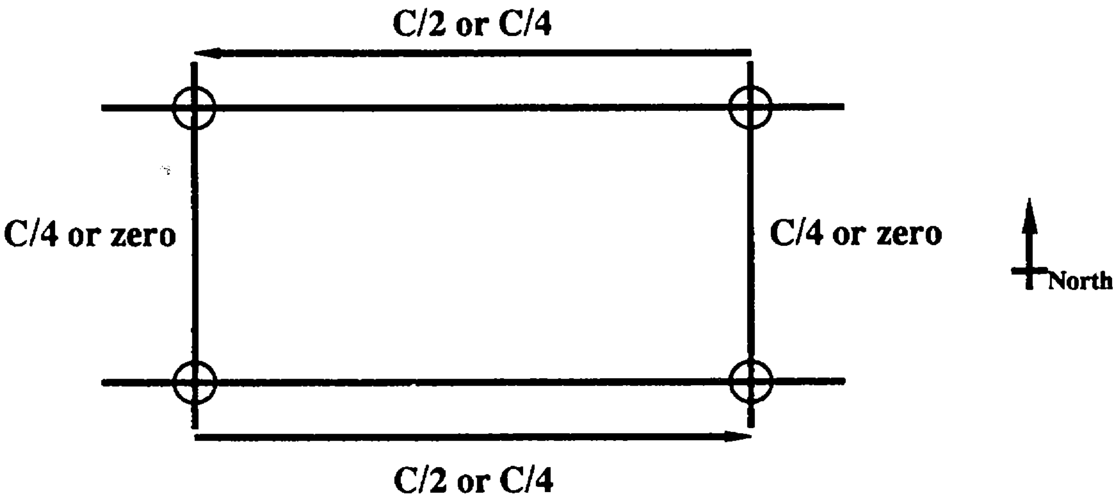
+ the design of the diamond has to take the coordination needs of the dominant flows into account. Refer to Figure 8 for an illustration of how the signal spacings in the second configuration of the previous section (i.e. Figure 3) has signal offset issues imbedded within it.

The interaction of
+ design
+ signal parameters
+ dominant flows
thus becomes an issue to consider.

Again, the literature does not provide specific enough guidance in this area.

c. Signal Timing and Optimization

The available information on this item is contained in Section 5 of this report. Alternative designs are also reported in Section 5.



1. The values indicated are for offsets, and their preferred settings depend upon the dominant flows to be served.
2. The geometry (spacing) of the four "corners" of the diamond depends upon the required offsets. The selection of the diamond configuration itself is thus influenced.

FIGURE 8

INFLUENCE OF DOMINANT FLOWS ON DIAMOND LAYOUT

The information is rather complete, and shows great creativity in (1) design concepts to remedy specific acute problems, and (2) signal timing to meet the needs of certain classes of diamond interchanges and traffic patterns.

3. CURRENT PRACTICE AND EXPERIENCE

3.1 Current Practice

This section describes the information obtained during the telephone conversation with agencies in different cities regarding the current practices in diamond interchanges.

Chicago
A two phase pattern with permitted left-turns or a three phase pattern with permitted/protected left-turns are widely used in Chicago. Some of the interchanges provide double left-turn lanes, but their effectiveness is reduced due to the high number of accidents. The agency is recently inclined to practice more with the Texas pattern (4-phases with two overlaps).

Toronto
The same phasing patterns, as the ones in Chicago, are applied in Toronto. The dominant characteristics of the diamond interchanges are: (1) the single left-turn lane and (2) the double or triple off-ramps which flare to four lanes at the stop line. It should be noted that there are not many diamond interchanges in Canada and the partial cloverleaf is dominant.

Los Angeles
Most of the diamond interchanges are without frontage roads with double or triple lane off-ramps (9-10 feet each lane). The three phase operation dominates with the sequence of phasing depending on the relative flows. To avoid storage problems a minimum spacing of 300 feet is recommended.

Texas
The four phase with two overlaps (or six phase) pattern is the one widely used in Texas. It minimizes the storage problem in the internal approaches, but usually requires a longer cycle length and with heavy frontage road traffic the delay is increased.

Detroit
Most interchanges are with service roads and the same phasing patterns like the ones used in Chicago are applied.

While this is not an all-inclusive survey, it does reflect the range of current operational experience and practice.

3.2 Insights from Current Practice

Based upon the information obtained from the literature and from a variety of users, plus the teams's own experience, the following "rules of thumb" can be distilled:

+ **Rule 1**

Two phase operation is better than three phase operation, so that situations (and designs) which avoid the need for three phases --- now or in the future --- are to be preferred.

Two phase operation often allows the diamond signal timing to be matched to progressive movement requirements along the cross arterial or the frontage road, rather than being disruptive to that pattern. It also reduces loss time and delay.

+ **Rule 2**
Because left turn conflicts lead to the need for three phases (for operations and safety), then it is better to turn significant opposed left turns into unopposed cross traffic whenever possible.

+ **Rule 3**
When opposed left turns are significant, multiple turn lanes are often needed. Multi-lane storage inside the diamond then becomes essential. Lengths of three hundred feet are often recommended to avoid difficulties.

+ **Rule 4**
When opposed left turns are significant, the four-phase operation or the six phase operation become valuable, since they provide a continuous movement in the internal approaches.

+ **Rule 5**
In all cases, maximizing the number of discharge lanes by "flaring" the approaches is very useful, to segregate movements and to reduce per-lane critical volumes.

+ **Rule 6**
Sophistication in signal timing ---- especially highly responsive control --- must be viewed with an awareness of regular patterns which must be regularly served.

These "rules of thumb" can be enhanced by the work recommended in the next section, and embodied into a set of guidelines and "case book" oriented to practicing operations and design engineers.

4. RECOMMENDATIONS FOR NEEDED WORK

There are three recommendations which have resulted from this work:

+ **Recommendation 1**
A thorough investigation is needed of the interactions amongst
  + design
  + signal parameters
  + dominant flows

in the context of the three elements highlighted on Page 4 of this report.

The investigation should consider (1) a set of different diamond interchange configurations, and (2) a set of dominant flow patterns, applied to each configuration.

By means of appropriate computational tools, the investigation should (1) quantify the traffic operational impacts in terms of capacity, delay, spillback and gridlock, and annualized cost, and (2) quantify the typical costs of the land acquisition and construction/reconstruction of the various alternative configurations.

The traffic computational tools should include use of the 1985 Highway Capacity Manual procedures, simulation, and traffic optimization models. Such computations should be accompanied by field observations of prototypical locations in each case, and should use field data from Arizona DOT and other sources.

In all cases, the most appropriate signal timing should be used, matched to the situation.

+ **Recommendation 2**
  The work undertaken under Recommendation 1 should be summarized in a set of guidelines and back-up case studies (a "case book") for practicing engineers, both traffic engineers and design engineers.

+ **Recommendation 3**
  The work on signal timing within diamond interchange configurations is extensive. Additional work on just this aspect of diamond interchanges should not be given a high priority at this time.

  Work related to Recommendations 1 and 2 might detail further signal-related work, such as questions related to detector location and use of "long loops" and area detection. However, establishing such needs should not be an objective under such work.

Recommendations 1 and 2 can be accomplished under one effort, with an estimated cost of $84,000. Table 1 summarizes the tasks and activities that could define such an effort. Table 2 presents the associated labor and other requirements, as well as a schedule.

TABLE 1

DEFINITION OF TASKS IN AN EFFORT IMPLEMENTING RECOMMENDATIONS 1 AND 2

Overall Objective

The overall objective is to provide guidelines and illustrative cases to practicing engineers on the interaction of

+ initial layout

and

+ future traffic problems

at interchanges which some variation of a diamond is considered, either in original design or in reconstruction work.

Specifically, the results are to focus attention on (1) the basic principles and rules of thumb, and (2) the matching of the design variation and specific layout dimensions to the traffic flows to be served, with traffic timing to be viewed as a consequence of these principles.

Information on "life cycle costs" which include land acquisition, construction, provision for future growth, and traffic operations over the design life of the interchange shall be addressed.

Task 1: Define the Configurations and Flow Patterns

The purpose of this task is to lay the groundwork for later tasks, by defining the configurations and flow patterns to be considered.

The diamond interchange configurations considered shall include all types specified in Figures 1-3, Figure 9, and Figures 13-14, as well as specific designs provided by Arizona DOT. A total of not more than 14 configuration variations shall be considered.

The flow patterns considered shall be those shown in Figure 7, with 2-3 volume sets considered for each flow pattern. The volume sets shall be representative of conditions in Arizona, now or in the future, and shall reflect the typical range over the various stages of a diamond interchange's life --- design volumes, extensive growth near the interchange, and other.

The signal timing (cycle length, number of phases, internal coordination, actuation) for the various cases shall be selected case-by-case, based upon current practice.

Task 2: Comment on Key Design Issues

The purpose of this task is to identify the "rules of thumb" as they should be applied to the various configurations, and to provide a "short list" of issues by which each design can be checked.

-more-

TABLE 1 (CONTINUED)

For each of the configuration-flow pattern combinations of Task 1, the following shall be identified and commented upon:

+ conflicting volumes, and critical lane volumes;

+ probable phasing requirements;

+ storage requirements;

+ advantages of number of discharge lanes;

+ dimensions as related to (1) traffic storage and (2) progressive movement of major flows, if any;

+ sensitivity of the design to future traffic growth;

+ sophistication of control needed.

This will be done on a single sheet for each case, in straight-forward, plain language.

These sheets will be checked against several (3-5) field situations of varying complexity.

Task 3: Review with Arizona DOT

The objective of this task is to have the team working on this project (even if an internal Arizona DOT group) formally meet with design and traffic engineers within Arizona DOT for a review of Tasks 1 and 2, in a one-day working session at the end of the second month of the project.

This meeting shall result in a list of some 15-20 cases being selected for detailed work in Tasks 4-6.

Task 4: Computation and Estimation of Traffic Impacts

The objective of this task is to investigate the critical lane flows, storage issues, overflow potential, and progression needs of each of the cases identified in Task 3.

The computation and estimation shall include:

+ critical lane flow analysis, using the techniques embodied in the 1985 Highway Capacity Manual;

+ simulation of the interchanges using a simulation model such as NETSIM;

+ signal timing and optimization programs as needed, to generate signal settings and mode of operation;

-more-

TABLE 1 (CONTINUED)

+ sensitivity analyses which give insight into the relative importance of number of lanes, dimensions, and other factors

The effort shall result in (1) general insights for Task 6, and (2) specific numeric illustrations for the "case studies" to be included in Task 6.

As part of this task, the use of the above tools shall be illustrated in an on-site orientation session in which a team member will use the tools with Arizona DOT engineers on a personal computer. This session will be an informal working session of some 4-7 attendees, over 3-4 days.

Task 5: Cost Estimation

The purpose of this task is to identify costs and demonstrate an economic analysis which would consider

+ land acquisition costs
+ construction costs
+ traffic operations costs
  - delay
  - operations and maintenance

in both present worth and annualized worth (i.e. annualized costs) approaches, so that engineers can be equipped to consider incremental design improvements versus traffic operations.

To accomplish this, several computations shall be executed for the cases identified in Task 3. At least two development scenarios shall be considered in each case. Emphasis will be on obtaining insight into "rules of thumb" on tradeoffs, for use in Task 6.

Task 6: Guidelines and Case Book

The purpose of this task is to prepare a set of guidelines and "rules of thumb" for practicing engineers, which can be of use in (1) considering alternative diamond interchange configurations in initial design or in reconstruction, and/or (2) evaluating future operational issues related to an existing situation or a proposed design.

The objective will be to have these guidelines and "rules of thumb" to be used. Therefore, they (1) shall be written in plain language, (2) should not exceed 50-70 pages in total, and (3) should include case studies of typical problems encountered. Because of this last item, part of the guidelines will be referred to as a "case book".

Task 7: Testing of Guidelines and Case Book

After distribution to practicing engineers within Arizona DOT for actual use (not just review comments), the document of Task 6 will be revised.

TABLE 2

ESTIMATED LABOR AND OTHER REQUIREMENTS FOR THE EFFORT OF TABLE 1

A. LABOR AND OTHER REQUIREMENTS

+ Labor

	Task 1-3	4	5	6	7	Total p-m
Senior Engineer	0.4	0.4	0.4	0.7	0.3	2.2
Other Professional	0.7	1.5	1.0	0.4	0.2	3.8
Support Labor	0.4	1.8	1.6	0.4	0.2	4.4
						10.4 *

+ Travel

Task 2 3 persons, field inspections
Task 3 2 persons, 2 days, Arizona DOT
Task 4 1 person, 4 days, Arizona DOT
Task 7 1 person, 1 day , Arizona DOT

+ Other

Availability of TE tools, IBM AT or equivalent
General M&S
Report and graphics

Estimated Cost = $ 84,000.

B. SCHEDULE

TASK	MONTHS
1-3	1-2
4	3-5
5	6-8
6	9-10
7	15-16

* This can be increased to 12.5 p-m to 15.0 p-m total by use of a graduate fellow in a university setting, in place of certain support labor.

5. CASE STUDY: CONSIDERATION OF ONE DESIGN

As one element of the project, comments were to be provided on the specific design shown in Figure 9. This design was provided as a case study by Arizona DOT as part of the contract.

In considering this design concept, the observations from Section 3.2 ("Insights from Current Practice") and from Section 2.2 ("Principal Conclusions") will be cited.

Given that physical constraints or economics prevent a reconstruction of the arterial, then this design is in excellent conformance with the principles which were derived from the state of the art and current practice:

+ extra lanes are provided on the highway bridge, to store left turners in both directions;

+ the ramps are flared to maximize the number of discharge lanes;

+ the arterial itself is flared, to remove the right turners (and the left turners) from the through lanes;

+ the design is aware of the signal considerations, as evidenced by the notes on the drawing.

Indeed, the design assures efficient use of the bridge left turn lanes by beginning the restricted use lanes in advance of the bridge structure.

Note that "Rules" 3 and 5 from Section 3.2 were invoked above.

However, the design shown in Figure 9 will logically require three phase operation for left turns from dual turn lanes, thereby (1) constraining the range of cycle lengths and (2) increasing the stop time --- and delay --- to through traffic on the arterial, unless those movements arrive only on the arterial main street green.

That is, "Rules" 1 and 2 from Section 3.2 must be considered; in this case, physical and economic considerations may preclude options such as shown in Figures 3 and 6.

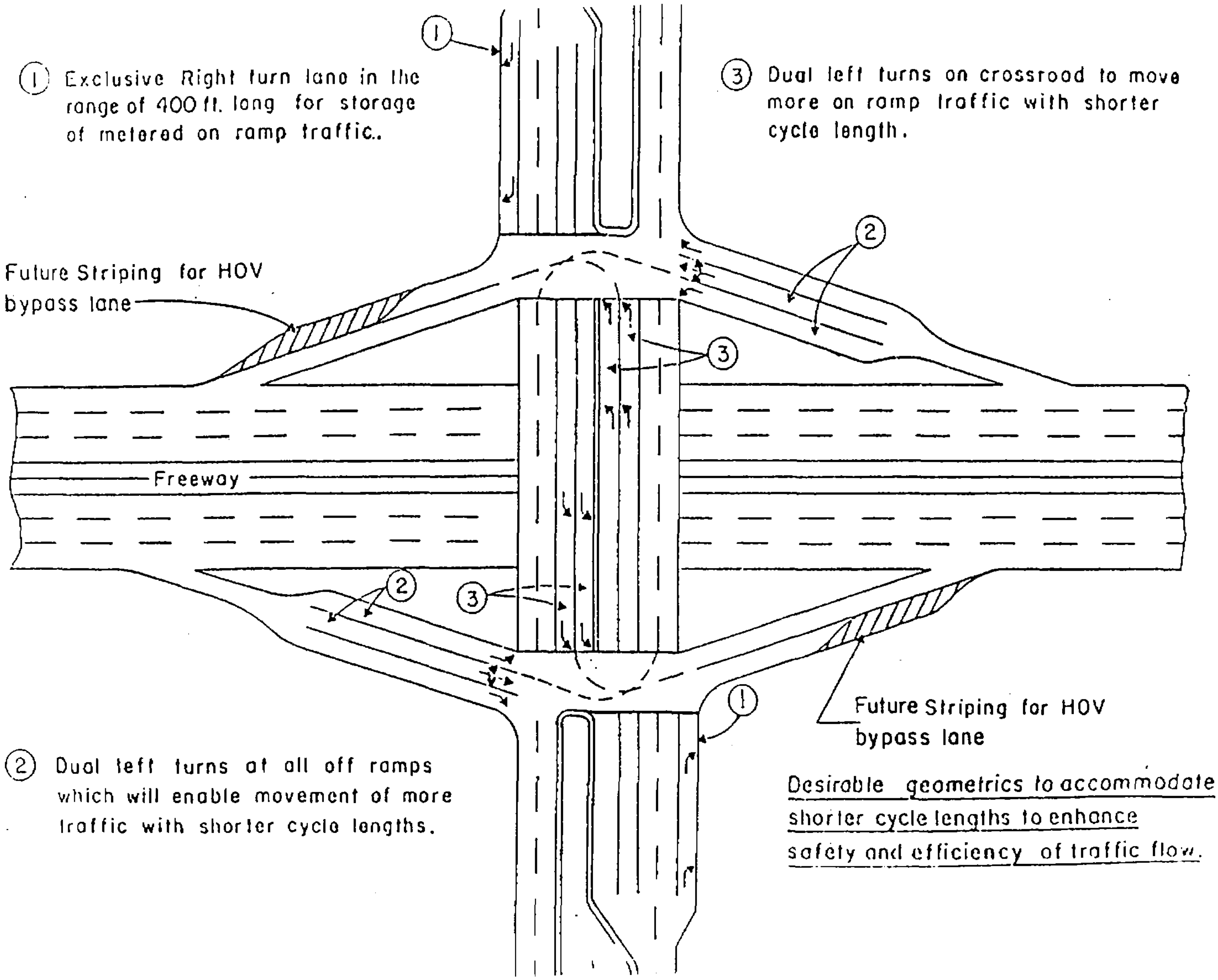


FIGURE 9

DESIGN PROVIDED AS A CASE STUDY BY ARIZONA DOT

To illustrate the sensitivity of the design to flow patterns and design detail:

+ Figure 10 shows a set of flow patterns/volume levels. These were applied with and without the flared ramps, for emphasis.

  Two cycle lengths were considered [70 and 90 seconds], each with three phase operation;

+ Table 3 summarizes the resultant v/c ratios, delay, and critical lane volumes;

+ Figure 11 shows an alternative design [which may be infeasible in this particular site, as already cited]. Table 4 summarizes the same statistics, for a cycle length of 70 seconds and two phase operation.

The comparison of the information in Tables 3 and 4 illustrates the traffic operations information which can go into the overall evaluation cited in the recommendations of Section 4.

6. LITERATURE REVIEW OF SIGNALIZATION AT DIAMOND INTERCHANGES

For any type of diamond interchange, the following characteristics prevail for the selection of the appropriate control:

+ Configuration (Full,Split,Half,etc.);

+ Length of ramps;

+ Distance between ramp intersections;

+ Number of lanes at the arterial and the ramps;

+ Directional traffic volume at the arterial and the ramps.

This section reviews the literature associated with diamond interchanges, and provides one of the bases for the summary of Section 2.1.

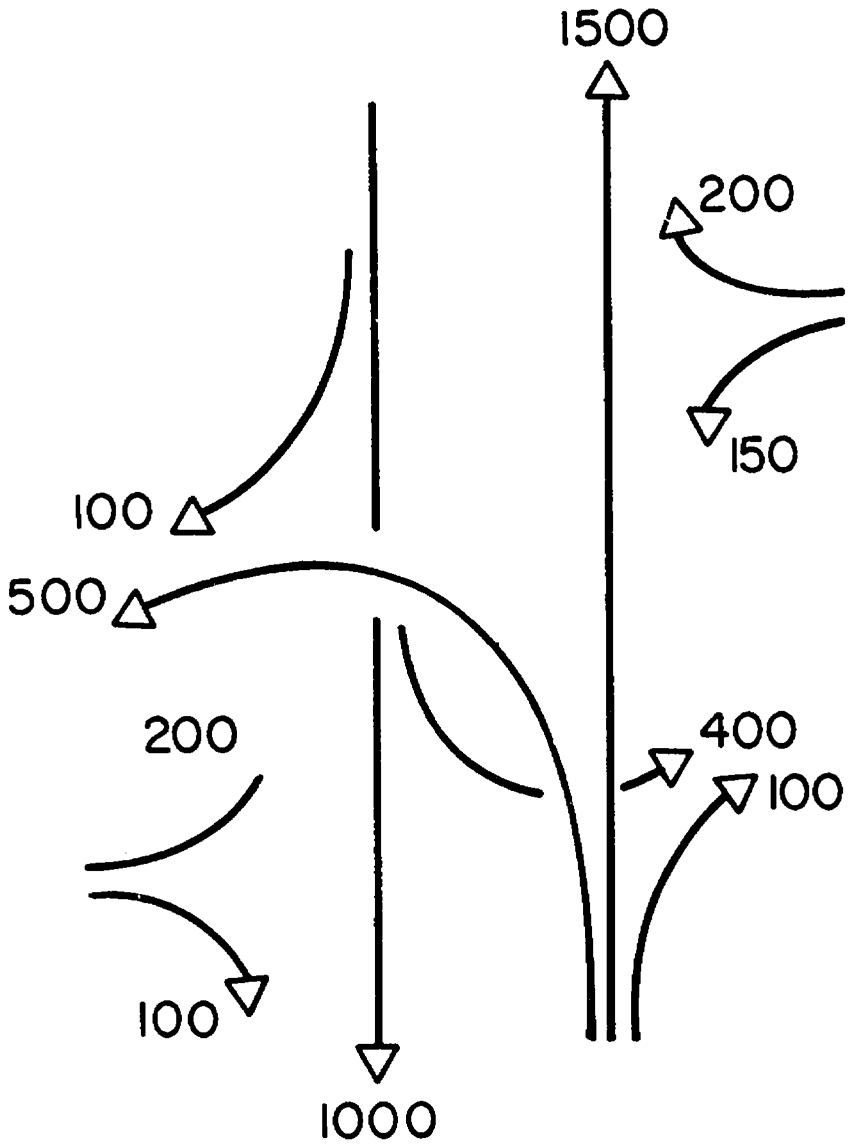


FIGURE 10
TWO SCENARIOS FOR FLOW PATTERN AND VOLUME
FOR FIGURE 9 CASE STUDY

TABLE 3

SUMMARY OF STATISTICS RELATED TO EVALUATION OF FIGURE 10 CASE

		FLOW PATTERN FROM FIGURE 10					
		Ramps Flared			Ramps Not Flared		
		v/c	Delay sec/ veh	Critical Lane Volume	v/c	Delay sec/ veh	Critical Lane Volume
C = 70 Seconds							
UPPER PORTION							
NB	Thru	0.66	3.8		0.82	10.3	
	Left	0.72	21.0	556	0.92	35.4	556
SB	Thru	0.72	16.6	1111	0.92	29.7	1111
	Right	0.17	12.5		0.22	17.0	
WB	Left	0.27	18.0				
WB	Right	0.72	25.4	222			
WB	All				0.92	35.0	389
All		0.72	12.1	---	0.92	22.3	---
LOWER PORTION							
NB	Thru	0.78	7.7	1667	1.00	28.3	1667
	Right	0.12	3.3		0.16	5.9	
SB	Thru	0.38	1.8		0.48	6.8	
	Left	0.78	25.6	444	1.00	55.2	444
EB	Left	0.78	32.1	222			
EB	Right	0.78	38.8				
EB	All				1.00	57.3	333
All		0.78	10.4	---	1.00	27.0	---

-more-

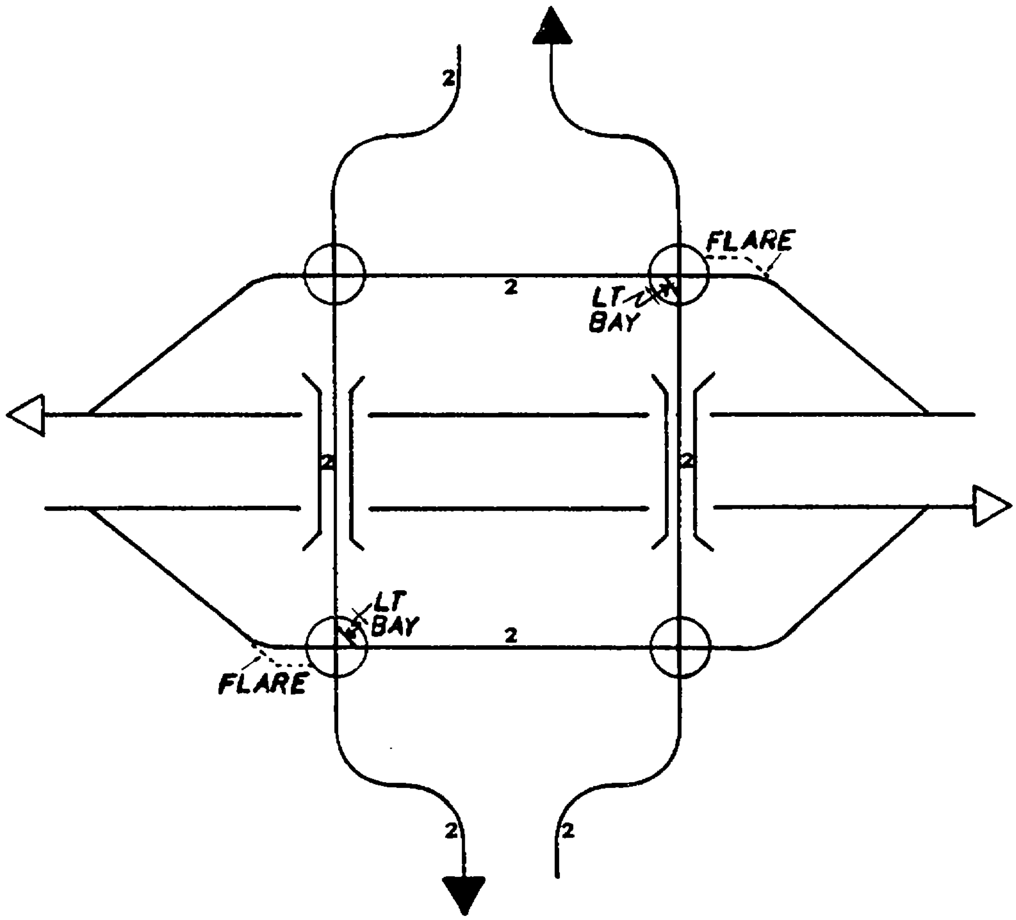
TABLE 3 (CONTINUED)

		FLOW PATTERN FROM FIGURE 10					
		Ramps Flared			Ramps Not Flared		
		v/c	Delay sec/ veh	Critical Lane Volume	v/c	Delay sec/ veh	Critical Lane Volume
C = 90 Seconds							
UPPER PORTION							
NB	Thru	0.65	4.4		0.81	12.1	
	Left	0.70	25.6	556	0.89	37.8	556
SB	Thru	0.70	19.8	1111	0.89	31.9	1111
	Right	0.16	15.3		0.21	21.1	
WB	Left	0.26	22.7				
WB	Right	0.70	29.8	222			
WB	All				0.89	34.4	389
All		0.70	14.5	---	0.89	24.1	---
LOWER PORTION							
NB	Thru	0.75	8.3	1667	0.97	25.7	1667
	Right	0.12	3.8		0.15	7.1	
SB	Thru	0.37	1.8		0.48	8.2	
	Left	0.75	30.3	444	0.97	54.2	444
EB	Left	0.75	37.0	222			
EB	Right	0.75	42.6				
EB	All				0.97	53.9	333
All		0.75	11.7	---	0.97	25.8	---

Notes:

1. Direction "north" is arbitrarily assigned toward top of paper in Figure 9.

2. "Upper" is northmost part of interchange. "Lower" is southmost part of interchange.



Note:
This "alternative" may well
be infeasible at the location, and is
only presented for a sensitivity analysis.

FIGURE 11

AN "ALTERNATIVE" DESIGN FOR THE CASE OF FIGURE 9

TABLE 4

SUMMARY OF STATISTICS RELATED TO EVALUATION OF FIGURE 11 CASE

		FLOW PATTERN FROM FIGURE 11					
		Ramps Flared			Ramps Not Flared		
		v/c	Delay sec/veh	Critical Lane Volume	v/c	Delay sec/veh	Critical Lane Volume
UPPER LEFT PORTION							
SB	Thru/Right				0.75	6.5	1667
WB	Left/Thru				0.75	19.8	723
All					0.75	10.5	
UPPER RIGHT PORTION							
NB	Thru	0.74	4.4	1889	0.87	10.5	1889
	Left	0.51	3.7		0.60	7.3	
WB	Thru	0.24	18.0				
WB	Right	0.74	26.3	222			
WB	All				0.87	29.2	389
All		0.74	6.8		0.87	12.4	
LOWER LEFT PORTION							
SB	Thru	0.42	1.9	1111	0.58	6.2	1111
	Left	0.39	2.6		0.55	8.7	
EB	Thru	0.36	19.5				
EB	Right	0.42	20.2	111			
EB	All				0.58	14.3	333
All		0.42	5.2		0.58	8.2	
LOWER RIGHT PORTION							
NB	Thru/Right				0.94	11.6	2333
EB	Left/Thru				0.94	36.2	666
All					0.94	17.0	

Notes:

1. **Direction "north" is arbitrarily assigned toward top of paper in Figure 9.**
2. **"Upper" is northmost part of interchange. "Lower" is southmost part of interchange.**
3. **C = 70 seconds, two phase used.**

6.1 Problems at Diamond Interchanges

The problems associated with the selected type of control and the above characteristics can be identified as follows:

1. **External-Internal Spillback**
   This situation occurs when the capacity of the internal intersection can not process the traffic demand either from the off-ramp or from the external intersection. Refer to Figure 12.a.

2. **Left Turn Spillback**
   This problem occurs when the left-turn demand at the internal intersection exceeds the available capacity,resulting to blockage of the through arterial volume. Refer to Figure 12.b.

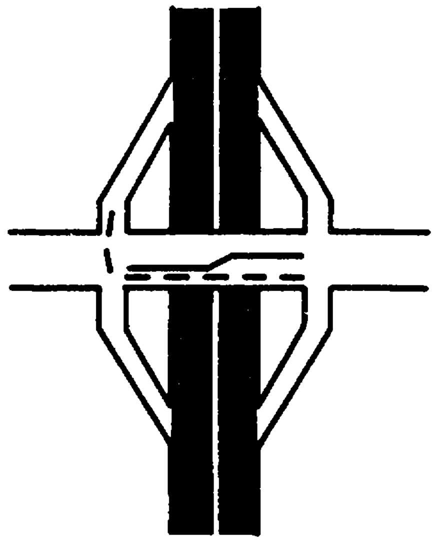
3. **Off-Ramp Spillback**
   This problem usually occurs when the capacity of the upstream intersection can not process the off-ramp traffic demand, resulting to blockage of the freeway exit. Reger to Figure 12.c.

6.2 Diamond Configurations

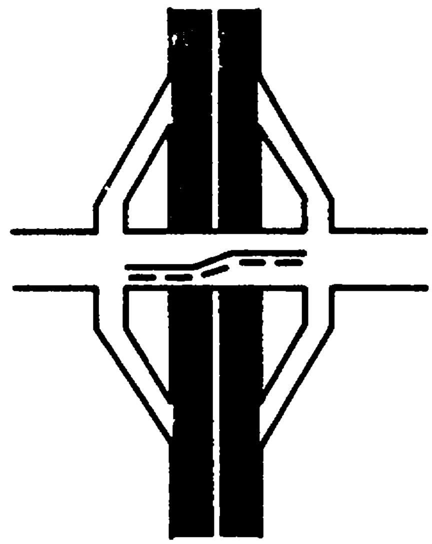
The most prevalent configuration is the Full diamond interchange with or without frontage roads, as originally illustrated in Figure 1.

Figure 13 illustrates newer design variations, including the "stacked diamond" which was recently developed for the improvement of the North Central Expressway in Dallas,Texas [2]. Each type has its own advantages and disadvantages, as reported in [2,3]. These may be summarized as follows:

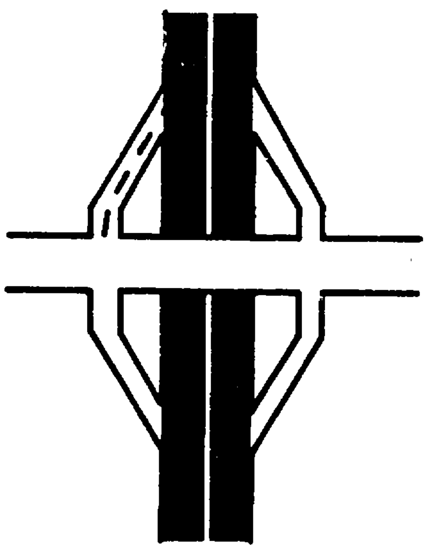
1. **Full Diamond**
   This type is appropriate for urban or suburban environments, where low to moderate high ramp volumes exist. Designs with frontage roads are likely in build-up areas, often as part of series of such interchanges along a freeway. The smooth operation of a Full Diamond will breakdown when the internal left turn volumes are high, since the available storage capacity is usually restricted.



a. External-Internal Spillback



b. Left-Turn Spillback

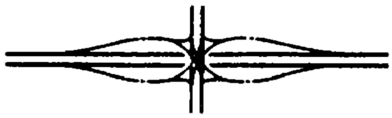


c. Off-Ramp Spillback

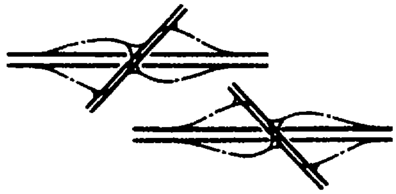
Source: Ref [1].

FIGURE 12

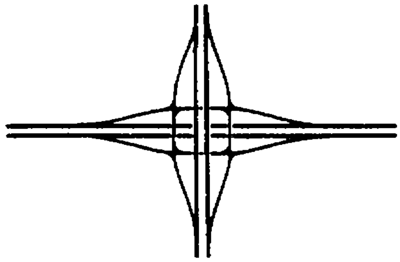
TYPES OF SPILLBACK



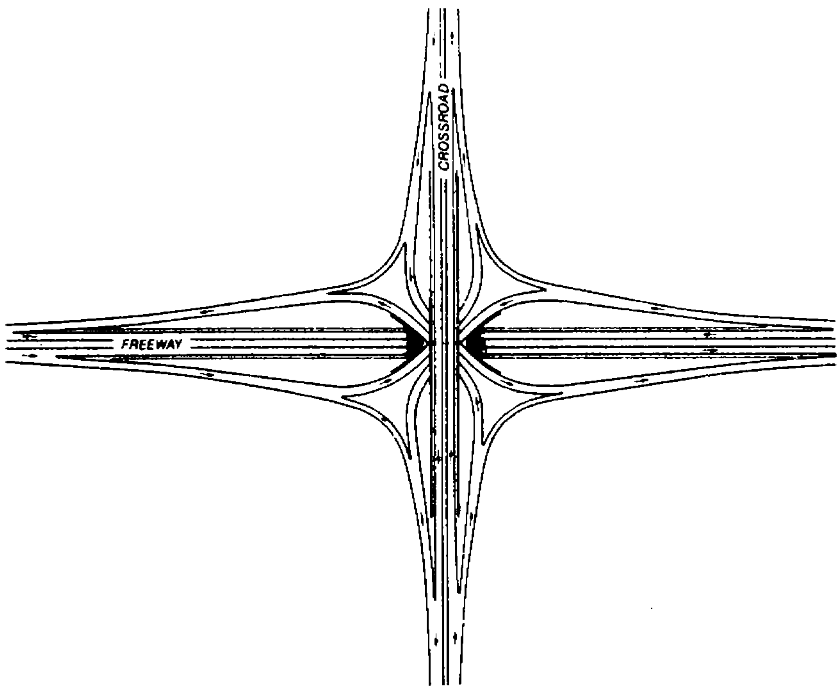
a. Single-Point Diamond



b. Three-Point Diamond



c. Three-Level Diamond



d. Stacked Diamond Interchange

Source: Ref [2].

FIGURE 13

NEWER VARIATIONS ON THE DIAMOND CONCEPT

2. **Split Diamond**
   This type is suitable for areas with multiple arterial streets and where frontage roads can be utilized. Conflict points are minimized and capacity increases with the use of a pair of one way cross-streets. Attention should be focus on the smooth operation of the four intersections to avoid spillback, especially off-ramp spillback.

3. **Half Diamond**
   This type is appropriate for areas with two-way arterial streets. An undesirable feature is that traffic leaving the freeway can not continue in the same direction by using the same interchange.

4. **Single-Point Diamond**
   This type is appropriate for confined urban or suburban environments where the freeway interchanges with a collector street or minor arterial (i.e. where the turning volumes are light to moderate and right-of way is restricted). Refer to Figure 13.a.

5. **Three-Point Diamond**
   This type is appropriate in moderate volume situations where right-of way is restricted in two of the four quadrants. Refer to Figure 13.b.

6. **Three-Level Diamond**
   It is a high capacity interchange appropriate for the intersection of a high volume arterial street and where access can be restricted for approximately 1000 feet in either direction of the freeway. Refer to Figure 13.c.

7. **Stacked Diamond**
   Was recently developed by J.P.Leisch. It is a three level arrangement with right-of way requirements slightly less than those of the conventional three-level diamond;its capacity is also somewhat higher. Refer to Figure 13.d.

Figure 14 illustrates a hybrid design in which two parts of a cloverleaf are used. This design has the advantage that the intersection points need only be two phase signals.

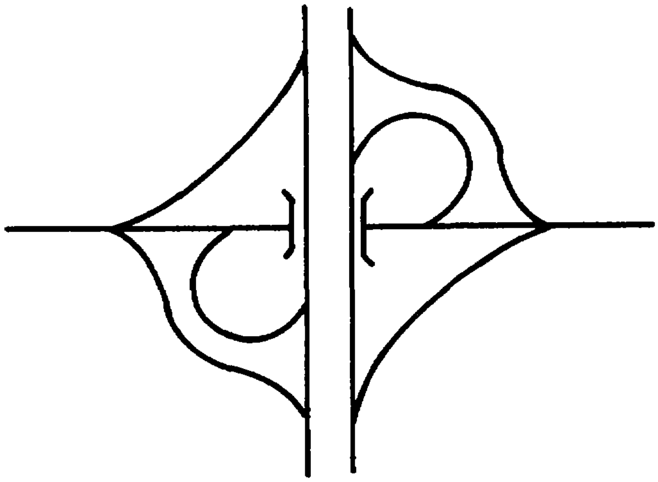


FIGURE 14

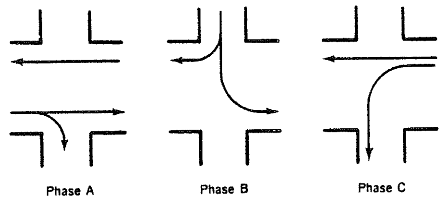
A HYBRID CONCEPT

6.3 Formation of Phase Sequence

Munjal addressed the basic concepts governing the phasing operation patterns of ramp intersections [4]. He presented an in-depth analysis of the potential combinations.

Each intersection can have three distinct phases without any conflict. These are illustrated in Figure 15, for the left ramp intersection. Phase A occurs when the green is given to the internal and external through movements.Phase B exist when the off-ramp movement has the green signal and phase C is taken place when the internal left turn movement is given a green signal.

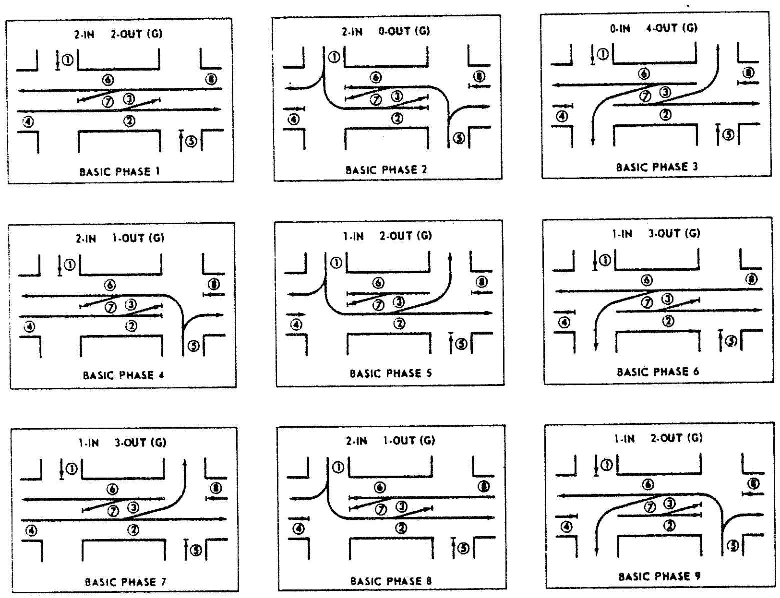
The three basic phases at each intersection can produce nine different combinations, as Figure 16 illustrates. Each intersection can have phase order ABC or ACB independently. The ABC phase scheme is called the leading left turn, while ACB is called the lagging left turn. Table 5 summarizes the possible phasing combinations for the two intersections.



Source: Ref [4].

FIGURE 15

THE THREE BASIC PHASES



Source: Ref [4].

FIGURE 16

NINE BASIC COMBINATIONS

TABLE 5

POSSIBLE PHASING COMBINATIONS

Left Intersection	Right Intersection	Description
ABC	ABC	lead-lead
ACB	ABC	lag-lead
ABC	ACB	lead-lag
ACB	ACB	lag-lag

6.4 Guidelines For Appropriate Phasing Selection

During the signal operation, inefficiency results (1) when cars in the internal approaches have to wait unnecessarily, (2) when there are no cars in the internal approaches to be served during the early seconds of green and/or (3) when cars from the external can not utilize the green time due to inadequate space in the diamond to accommodate them [4].

Traffic engineering literature has explored a variety of appropriate phasing patterns to reduce inefficiency in diamond interchanges. This subsection addresses the relative merits of the most important ones, with special focus to the 4-phase with overlaps.

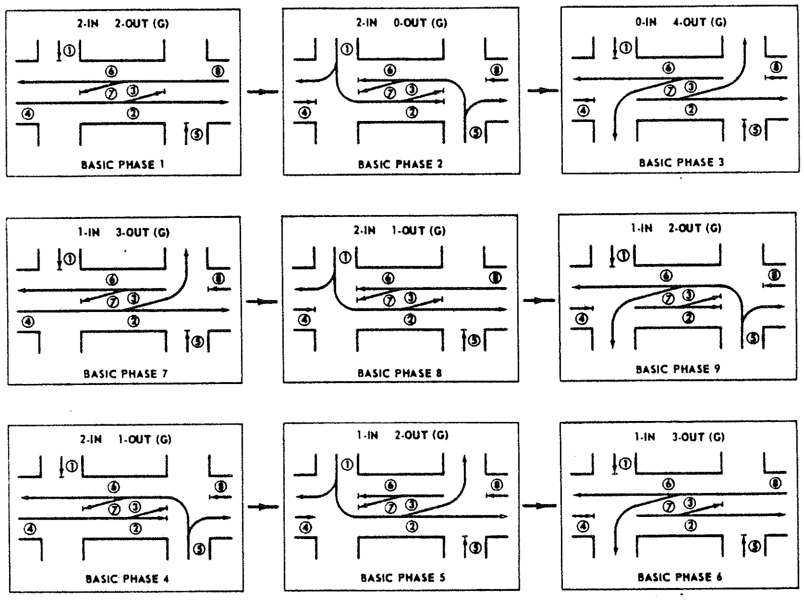
All the patterns which will be discussed can be accomplished by changing only one parameter (i.e. the offset). For the purpose of this report, an offset is defined as the difference between the green initiation of the external arterial through movements.

A. Three-Phase Patterns

Figure 17 illustrates the formation of lead-lead patterns for 0,1, and 2 phase length offsets, while Figure 18 illustrates the formation of lag-lag patterns for the same offsets.

A relative comparison between the two configuration will indicate the following:

1. For a zero offset, phasing is symmetrical for both directions of traffic and therefore this pattern will be advantageous for balanced volumes, since the allocated time is equal for the relative movements. Ref [1] points out that "if the arterial through movement is "on" for a period greater than the one required to traverse the distance between the two intersections, left turn storage problems might arise." Therefore, the longer the distance between the ramps the better the operation.



0 phase offset

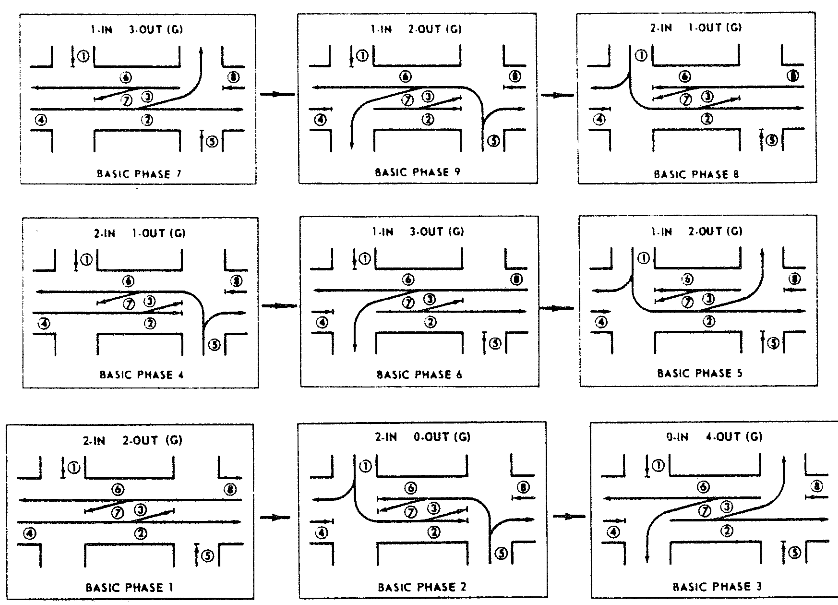
1 phase offset

2 phase offset

Source: Ref [4].

FIGURE 17

PHASING FOR LEADING LEFT TURNS



2 phase offset

1 phase offset

0 phase offset

Source: Ref [4].

FIGURE 18

PHASING FOR LAGGING LEFT TURNS

2. Both patterns are very efficient for heavy through movements and relatively light left turn movements due to the limited storage capacity of the diamond. Therefore these patterns are not recommended for diamond interchanges with frontage roads (where U-turn movements from the off-ramps and the frontage roads might be significant) or heavy arterial left turn movements.

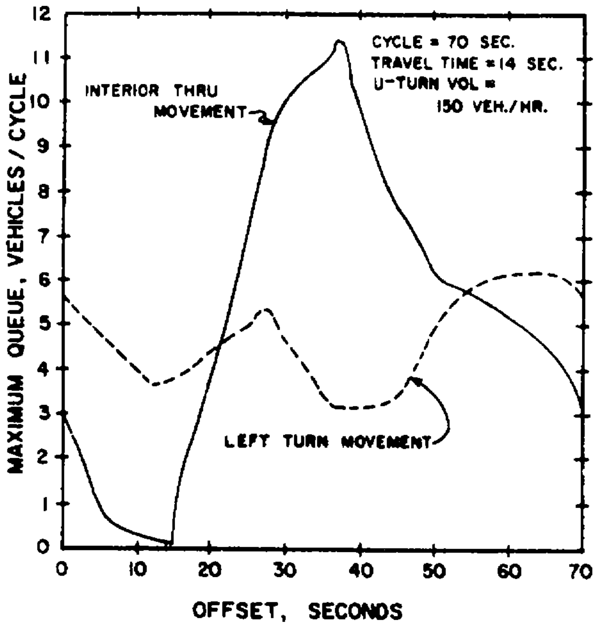
3. The lag-lag pattern, with a relative offset of zero percent [±10%] of the cycle length, produces delays which are comparable to the lead-lead patterns whenever the ramp movements are relatively light (less than 200 vph/ramp) and when the overall traffic demands do not exceed 20-40% of the saturation flow levels of the facility [5].

4. When the directional movements are not balanced, an offset between the two intersections must be considered. If the east-bound arterial and the south-bound off-ramp movements require more time than the west-bound and north-bound ones, a lead-lead pattern with 1 phase length offset or a lag-lag pattern with 2 phase offset are more appropriate.

The lead-lead or the lag-lag pattern should be accordingly selected when the traffic generated from the north-bound off-ramp or the west-bound external intersection create storage problems respectively. Figure 19 illustrates the variation of the queue length, for an east-bound movement, as a function of the offset for a lead-lead pattern. For an offset of approximately 15 seconds or one phase length [e.g.in a 60 seconds cycle], the maximum queue is reduced.

5. In the absence of waiting vehicles in the internal approaches,the green time is not utilized as it should.

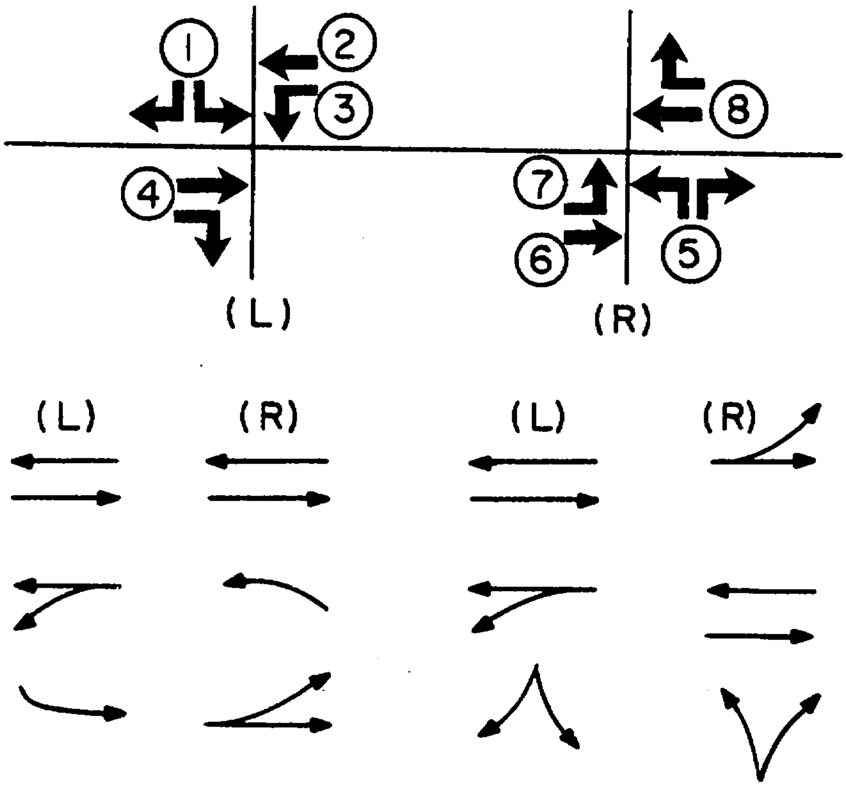
Figure 20 depicts two additional configurations; a lead-lag pattern (Figure 20.a) and a lag-lead pattern (Figure 20.b). The lead-lag pattern is suitable for balanced arterial through movements and for substantial U-turn volumes.The lag-lead pattern is appropriate for balanced off-ramp flows and unbalanced arterial movements.



Source: Ref [6].

FIGURE 19

VARIATION OF MAXIMUM QUEUE LENGTH WITH OFFSET



a. Lead-Lag

b. Lag-Lead

FIGURE 20

TWO ADDITIONAL PATTERNS

B. Four Phase Patterns

Figures 21 and 22 illustrate configurations which belong to the general family of the 4-phase patterns with or without overlap. The nearly continuous movement of traffic in the internal intersections and the satisfactory operation under heavy arterial left turn conditions or off-ramp U-turn traffic have established these patterns as among the most recommended. The majority of the pertinent literature has focused to the overlap operation. A description of the prevailing characteristics is presented in the following section.

C. Operation with 2-Overlap Phases

The major advantage over the 4-phase without overlap is the efficient utilization of the green time by means of the overlapping phase. Woods [7] indicated that "since the overlapping signalization was developed to increase capacity, the average delay might be greater than with non overlap signal systems, but that the maximum delay should be reduced." The performance and the potential applications depend on the length of the overlapping phase. In this report, both the overlapping phases assumed to be equal.

6.5 Critical Equations

The operation of the overlapping signalization is controlled by the following equations, where the subscripts are refering to the movements illustrated in Figure 23:

$$G_1 + G_3 + G_4 = C \qquad [1]$$

$$G_5 + G_7 + G_8 = C \qquad [2]$$

$$G_3 + G_7 = C - \phi \qquad [3]$$

$$G_1 + G_4 + G_5 + G_8 = C + \phi \qquad [4]$$

where:

G_i = Green plus amber time on approach i in sec.
ϕ = Total overlap phase in sec [$\phi_1 = \phi_2$]
C = Cycle Length in sec.

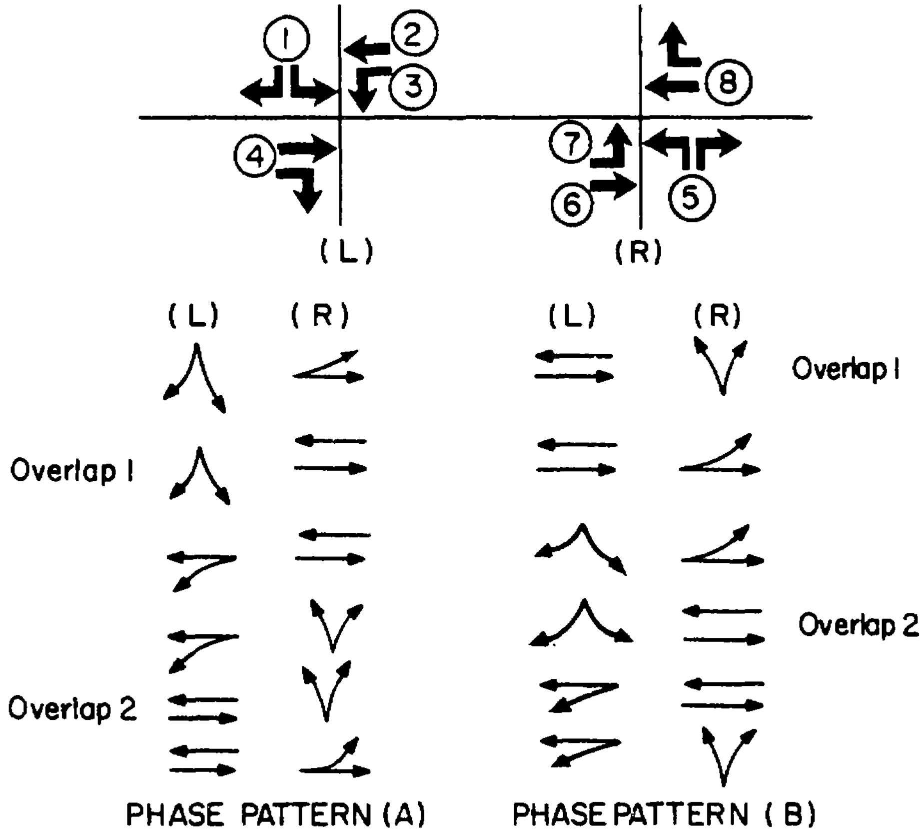


FIGURE 21

FOUR PHASES WITH OVERLAP

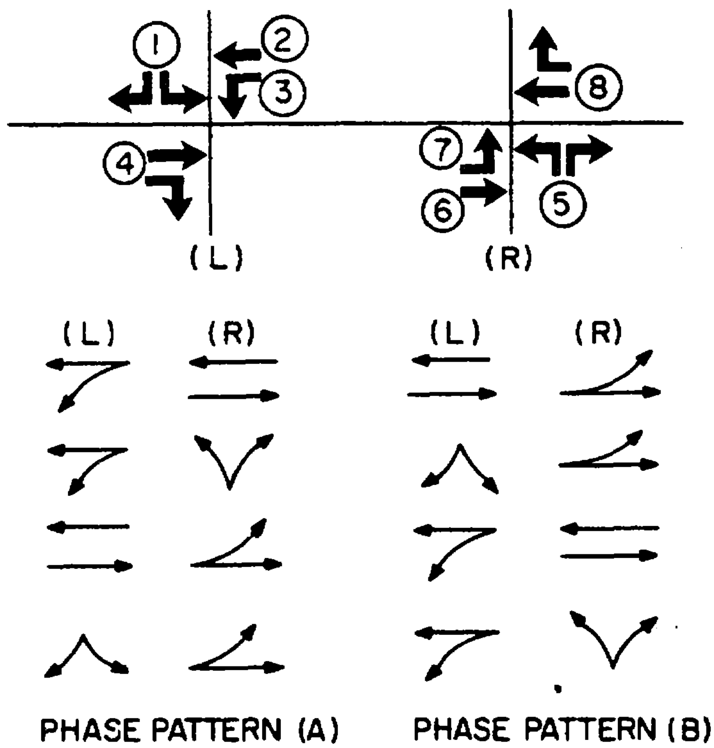


FIGURE 22

FOUR PHASES WITHOUT OVERLAP

Equations 1 and 2 describe the individual operation of each intersection, while Equations 3 and 4 link the two intersections, and apply as restrictions for the allocation of the green time. Because the total available time for the internal left turn movements is predetermined for a given cycle length and overlap phase, they must be proportioned so that the remaining time at each individual cycle, required for the external movements, is in proportion to the time needed at both intersections [8].

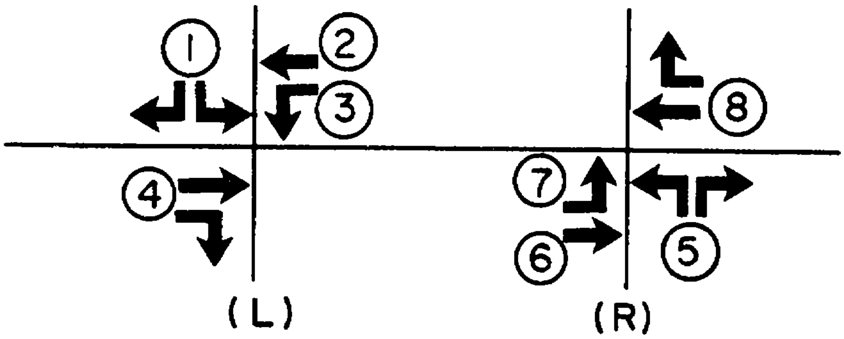


FIGURE 23

DIAMOND INTERCHANGE MOVEMENTS

6.6 Cycle Length

Woods [7] suggested that a 60 seconds cycle is the practical lower limit for an overlap pattern. This is in accordance with the indication of [9] that the signal performance will seldom be improved by decreasing the cycle below 70 seconds during peak hour conditions. Equation 5 cites the relationship between required and available time by means of the saturation ratio for the interchange.

$$X = Y * C / [C + \phi - L] \qquad [5]$$

where:

X = Saturation ratio for the interchange.

Y = The sum of the flow ratios $(v/s)_i$ for the external approaches.

L = The total lost time for the external approaches

ϕ = Total overlap phase in sec.

C = The cycle length in sec.

Equation 5 indicates that when the overlap phase is greater than the lost time, the capacity of the external approaches increases. Under the same conditions, as the cycle length is reduced, the system becomes more efficient [i.e. the percentage of effective green per cycle increases.]

6.7 Minimum Length of Overlap

Ref [8] indicates that a phase overlap of 10 seconds [total overlap of 20 seconds] appears to be the least value that can take full advantage of the capability of the overlap signalization.

However, Ref [8] reports that overlaps of 10 seconds appear to be near the optimal for a wide range of conditions, and that even overlaps of 7 seconds will operate effectively at peak hour cycle lengths.

6.8 Minimum External Volumes

Assuming the minimum conditions for an overlap pattern [i.e phase length of 10 seconds, overlap phase 10 seconds and a cycle of 60 seconds] each of the external approaches can accommodate the following volumes:

1. **Overlap Volume**
   Considering that 10 seconds can discharge approximately 4 vehicles, a minimum volume of 240 vph is required.

2. **Total Volume:**
   For an external phase length of 15 seconds the minimum volume will approximately be 400 vph.

6.9 Effect of Minimum Phase Lengths

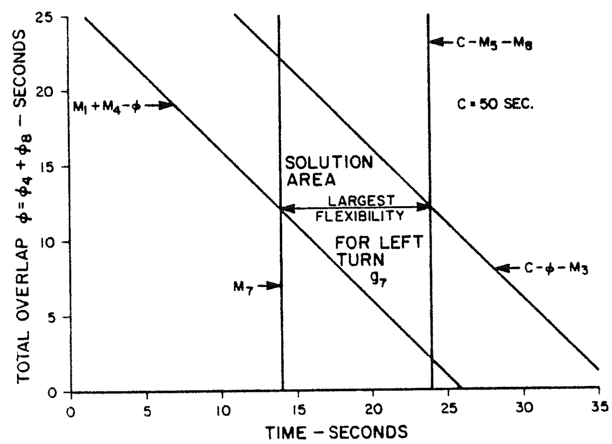
Predetermined minimum phase lengths [M_i] due to pedestrian phases or minimum vehicle-phases, constrain the allocation of green time. Figure 24 illustrates the constraint effects of the critical equations to the allowable green time for a left turn movement and how this phase flexibility is associated with the selection of the suitable overlap length. Ref [8] indicates four important items:

1. Minimum greens should not be selected without knowing the effects on signal operation. If the minimum greens are large and the cycle length is short, it might not be possible to compute satisfactory phase lengths.

2. There exist an optimal overlap that gives the greatest flexibility in signal phase allocation for a given set of minimum greens.

3. The solution area can be increased by increasing the cycle length, but the external movement capacities are reduced.

4. Increasing the overlap length, the phase flexibility is reduced.



Source: Ref [8].

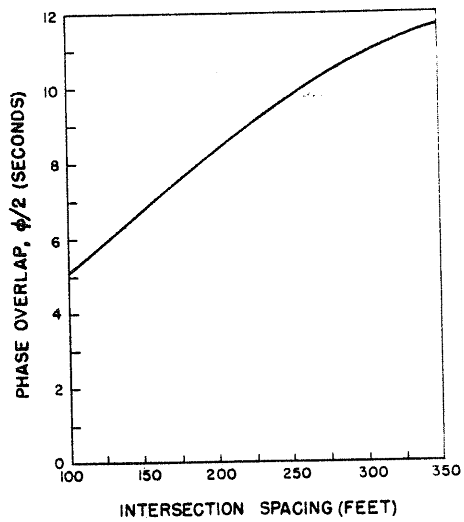
FIGURE 24

OVERLAP AND MINIMUM GREEN RELATIONSHIPS

6.10 Intersection Spacing

To obtain the desired 10 seconds overlap, a minimum spacing of approximately 260 feet is required [7]. Figure 25 illustrates the effect of varying spacing between intersections, showing that the overlap phase increases with increasing spacing as it was expected. Figure 26 shows the effect on average delay at the interchange, due to variations in the cycle length and the total overlap (equivalent intersection spacing given by Figure 25), assuming constant minimum phase of 16 seconds [9].

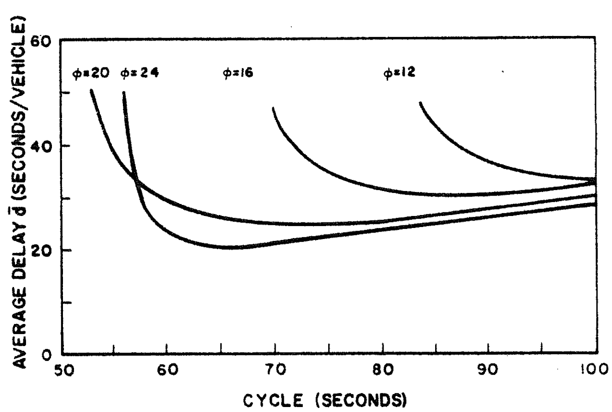
For the same cycle the average delay increases with decreasing overlap length and this can be attributed to the decreasing external capacity. For cycles less than 70 seconds, an increase in the overlap phase does not necessarily imply a decrease in delay.



Source: Ref [9].

FIGURE 25

VARIATION OF OVERLAP AS A FUNCTION OF SPACING



Source: Ref [9].

FIGURE 26

AVERAGE DELAY VERSUS SPACING AND CYCLE

6.11 Interchange Delay

Figure 27 illustrates the relationship of the interchange delay as a function of the offset and the phasing pattern, by using the PASSER III computer program, as reported by [10]. Exterior delay was calculated in this reference by using Webster's formula, while interior delay by using the delay-offset technique. Average delay per vehicle was calculated by combining the effects of the two components. The phase codes are related to the phasing patterns according to:

1: lead-lead,
2: lag-lag,
3: lead-lag,
4: lag-lag
1A: 4-phase with overlaps.

Minimum delay results were also reported [6] for U-turn volumes of 50 vph and 150 vph for a range of cycle lengths and intersection spacings. The results are presented in Tables 6 to 8. The following interesting points should be noted:

1. It is evident that an optimal phasing can not directly identified before all the candidate patterns, for a specific set of conditions, are considered.

2. For the same cycle as the travel time increases the minimum delay decreases.

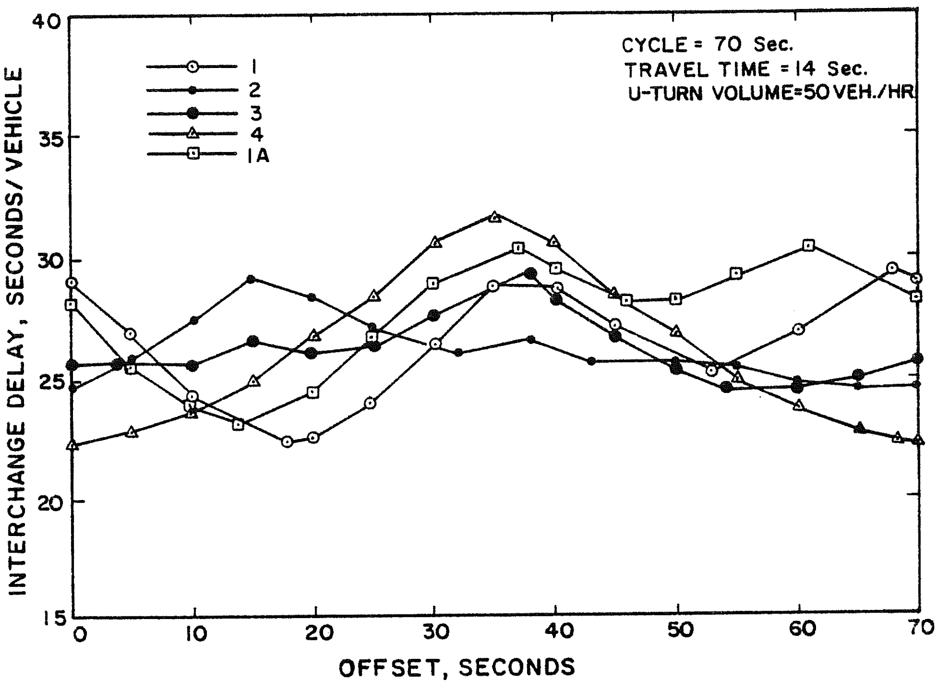
3. A lead-lead phasing results to lower minimum delays than a four phasing with overlaps.

4. As the travel time increases, the difference between the resulting minimum delay is decreased.

5. For light U-turn volumes a lag-lag pattern results optimal minimum delay.

6.12 Assignment of Walk Interval

The assignment of the walk intervals depends on the phase sequence and whether right-on-red are permitted. Table 9 illustrates preferred walk interval assignments, according to [5].



Source: Ref [6].

FIGURE 27

INTERCHANGE DELAY VERSUS OFFSET

TABLE 6

MINIMUM DELAY FOR INTERCHANGE AND PHASE CODES 1 AND 1A FOR 50 V.P.H. U-TURN VOLUME

Travel Time, Seconds	Cycle Length, Seconds	Minimum Interchange Delay, Sec./Veh.		
		Optimum Phasing	Phasing Code 1	Phasing Code 5
6	60	20.85	21.89	23.95
6	70	23.17	25.33	27.52
6	80	25.68	27.85	31.03
10	60	19.92	20.30	21.28
10	70	22.92	23.61	24.81
10	80	25.95	26.93	28.31
14	60	19.35	19.35	20.00
14	70	22.05	22.22	23.07
14	80	24.80	25.42	26.31

Source: Ref [6].

TABLE 7

MINIMUM DELAY FOR INTERCHANGE AND PHASE CODES 1 AND 1A FOR 150 V.P.H. U-TURN VOLUME

Travel Time, Seconds	Cycle Length, Seconds	Minimum Interchange Delay, Sec./Veh.		
		Optimum Phasing	Phasing Code 1	Phasing Code 5
6	60	22.75	25.32	26.65
6	70	25.02	28.87	29.97
6	80	27.71	31.81	33.75
10	60	23.93	23.54	24.10
10	70	26.99	27.24	28.04
10	80	28.72	30.85	31.94
14	60	22.57	23.40	22.82
14	70	26.28	26.28	26.28
14	80	29.35	29.35	29.83

Source: Ref [6].

TABLE 8

MINIMUM DELAY PHASE CODES FOR 18 INTERCHANGE SIGNALIZATION PROBLEMS

Travel Time, Seconds	Cycle Length, Seconds	Optimum Phase Codes: U-Turn Volume, 50 V.P.H.	Optimum Phase Codes: U-Turn Volume 150 V.P.H.
6	60	2,3	2,3
6	70	2,3	2,3
6	80	2,3	2,3
10	60	4	1
10	70	4	2,3
10	80	4	2,3
14	60	1	4
14	70	4	1,1A
14	80	4	1

Source: Ref [6].

TABLE 9

ASSIGNMENT OF WALK INTERVALS

Pedestrian Crossing Location	Phase Sequence	Right-on-Red Permitted	WALK Interval Assignments
Arterial	ABC or ACB	Yes or No	Phase B
On-Ramp	ABC or ACB	Yes or No	Phase A *
Off-Ramp	ABC	Yes	Phase C **
Off-Ramp	ABC	No	Phase A or C
Off-Ramp	ACB	Yes	Phase A **
Off-Ramp	ACB	No	Phase A or C

* Phase B could also possibly be used if the pedestrians are alerted to the possible risk from off-ramp through-vehicles on non-frontage road interchanges.

** This allows less possibility of pedestrian conflicts with right turning vehicles.

Source: Ref [5].

6.13 Signal Control Type, Detectors, and Phasing

Research regarding this subject for diamond interchanges under different operational conditions is limited, with [11] being notable. The conclusions and recommendations of this study are reported verbatim in Tables 10 and 11 respectively.

This work had been based upon field studies at diamond interchanges having continuous one-way frontage roads rather than exit ramps. In reporting the field work, it was stressed that it was not possible to prove the actuated systems were equally fine-tuned, as there is no metric for this purpose. Therefore, the operational performance of three-phase and four-phase with overlaps should be viewed with that caution.

TABLE 10

CONCLUSIONS FROM REFERENCE 11 RELATED TO ACTUATED CONTROL AT DIAMOND INTERCHANGES

1. Single-pointed detection is the more cost-effective three-phase detection system because it provides the same effectiveness as does the more costly multi-point detection system.

2. Multi-point detection is the more delay-effective four-phase detection system. It provides more effectiveness but with a more expensive system. It's true cost-effectiveness is unknown.

3. Shorter cycle lengths are, in general, a desire attribute for isolated interchange control. Phase termination should be "snappy", with promt phasing termination becoming more critical as volume increases.

4. Four-phase control characteristically operates at a longer cycle length than does the three-phase for a given traffic volume, but provides superior internal progression within the interchange.

5. Three-phase control can produce less overall queueing delay than four-phase for the same volume and level of detection. In most cases, however, this lower delay arises at a price of undesirable secondary stops within the interchange.

6. Three-phase control can be a good phasing strategy under selective geometric, traffic and controll conditions. Three-phase works better when the interchange is wide and where there is a high proportion of through flow, either on the frontage roads and/or cross street. In most cases, three-phase requires the use of relative short cycle times with wider interchanges permitting better phase flexibility and smoother flow through the interchange.

7. Four-phase is an acceptable signal phasing stategy for typical urban interchange applications. Control stability and progressive flow are routinely provided but usually at a price of increased cycle length and overall interchange delay unless the control is finely tuned.

8. Single-point detection produces, in general , longer cycle lengths than does multi-point detection. The trend toward longer cycle times for single-point detection is greater for four-phase than for three-phase control. Multi-point detection also can become susceptible to producing long cycle lengths under some heavy volume conditions.

Source: Ref [11].

TABLE 11

RECOMMENDATIONS FROM REFERENCE 11 RELATED TO ACTUATED CONTROL AT DIAMOND INTERCHANGES

1. Single-point detection should be considered as basic system component for three-phase control.

2. Multi-point detection on the frontage roads should be considered as a basic system component for four-phase control.

3. Four-phase with overlap control should be considered as a viable alternative in all cases of isolated, diamond interchange control where one-way frontage roads exist.

4. Three-phase control should be considered as a viable alternative when any of the following isolated interchange control conditions exist:

    a. When there is a smnall percentage of left-turn traffic on the frontage ; or

    b. when the interchange has sufficient internal queue storage capacity to store traffic without locking-up the turning movements within the interchange ; or

    c. when the interchange experiences freeway exit ramp or frontage road backup affects freeway operation ; and

    d. the cycle length is kept short, phase termination snappy, and adequate visibility of the interchange signal operation exists.

5. Traffic control techniques should be considered for implementation at actuated diamond interchanges that delay phase calls and rapidly gap-out phases of lighter traffic in heavier traffic demand situations. At high-volume interchanges, control features such as traffic-responsive, variable timings may be desired to reduce delays and minimize phase max-out even for multi-point detection.

6. There is a need to develop standard field-test procedures for determining when an actuted diamond interchange controller unit is optimally fine-tuned to existing traffic conditions.

7. A traffic controller unit providing a combination of three-phase and four-phase operations should efficiently service a wide range of traffic and geometric conditions. The additional feature of providing improved progression along the cross street and/or frontage roads would be additional attractive feature.

Note: Ref [11] cautions that the recommendations apply only to isolated diamonds, with inside-to-inside, curb dimensions of 450 feet or less, with basic full-actuated traffic signal control and point detectors.

Source: Ref [11].

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